Artificial Evolution to Test and Challenge Complex Control Systems

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Overview

- Background: Design of Complex Systems
- Evolutionary Testing of Complex Systems

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Testing and Design

Understanding our Systems

- Ignorance

  (not knowing what you don't know)

2. The combinatorial nature of systems

   (too many parts)

   - Hardware, software, people, processes

3. Emergent phenomena

   (the parts interact)

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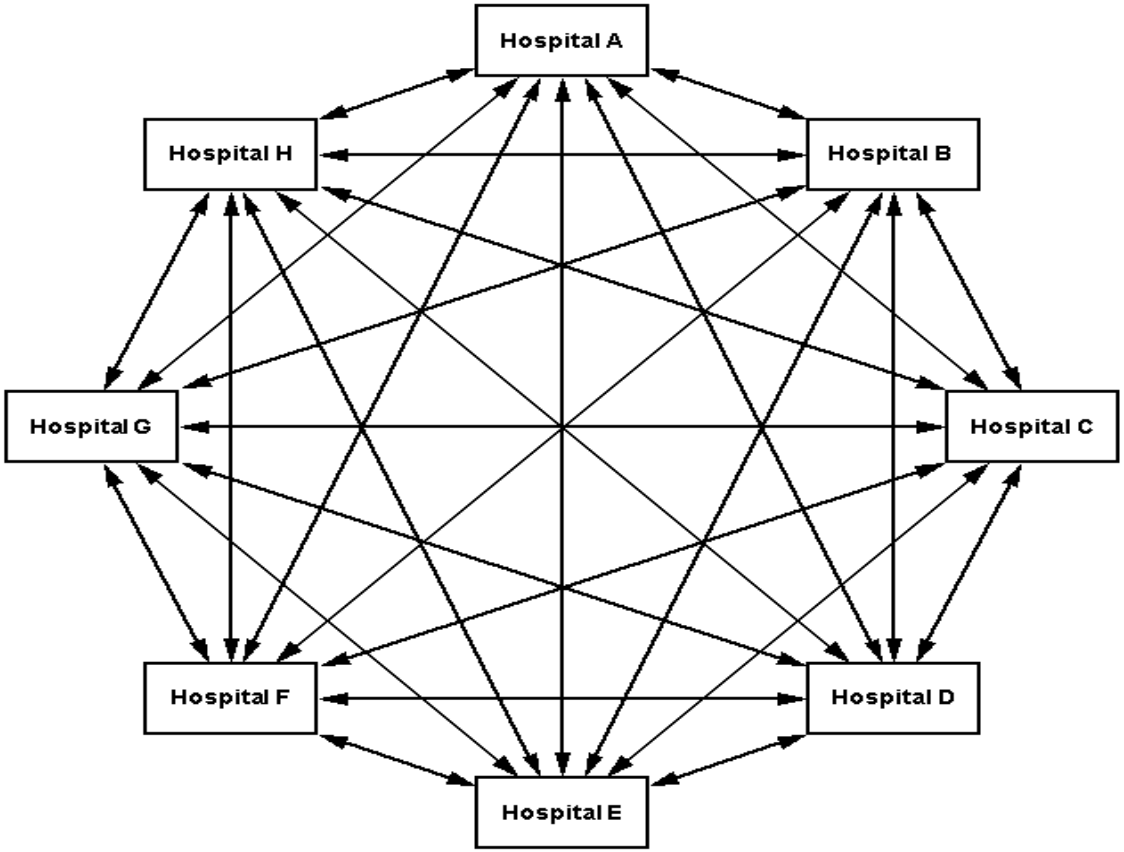
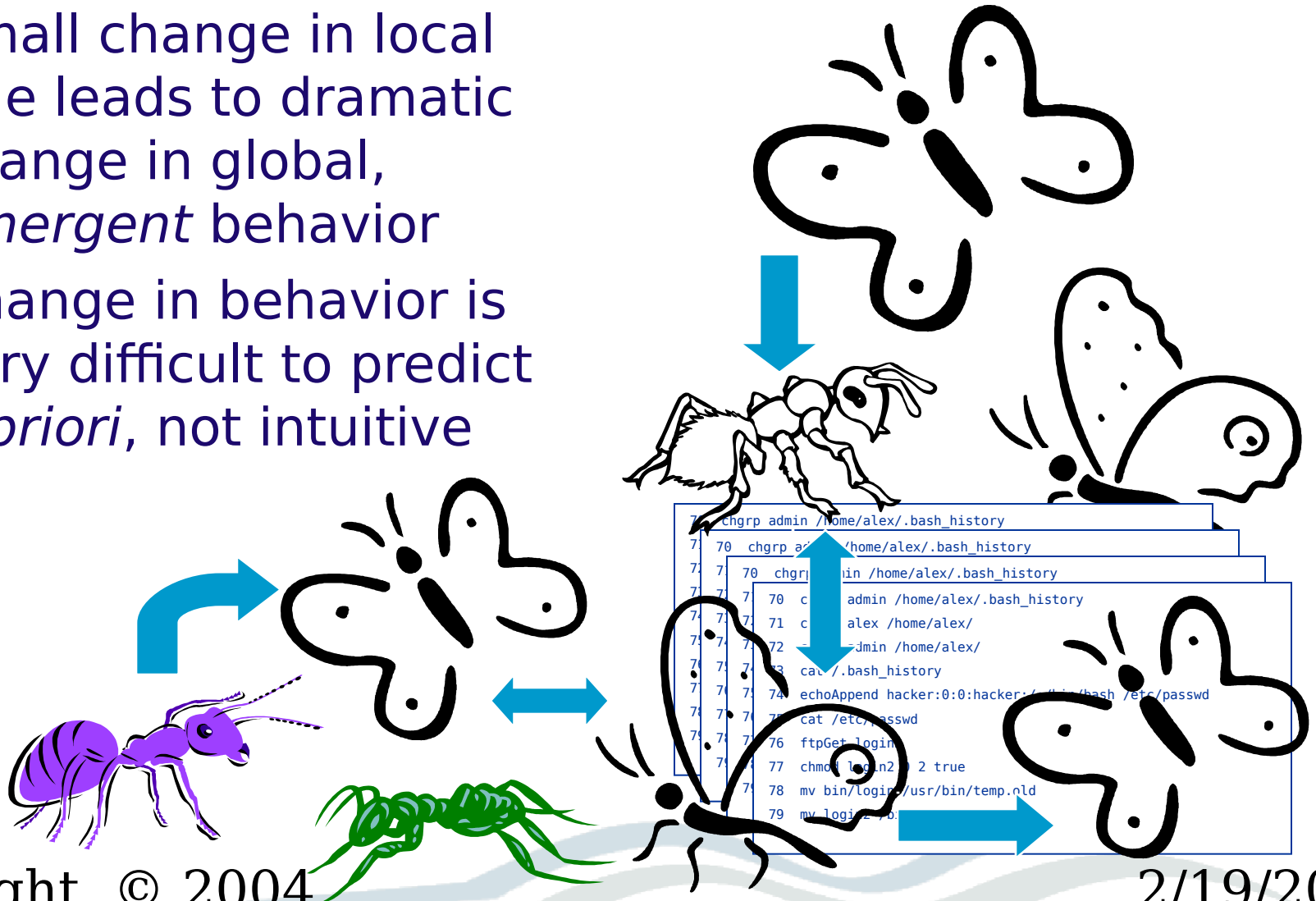
Combinatorial Problem



If every organization uses a different database schema, the interchange problem is combinatorial.

Emergent Behavior

- Small change in local rule leads to dramatic change in global, *emergent* behavior
- Change in behavior is very difficult to predict *a priori*, not intuitive



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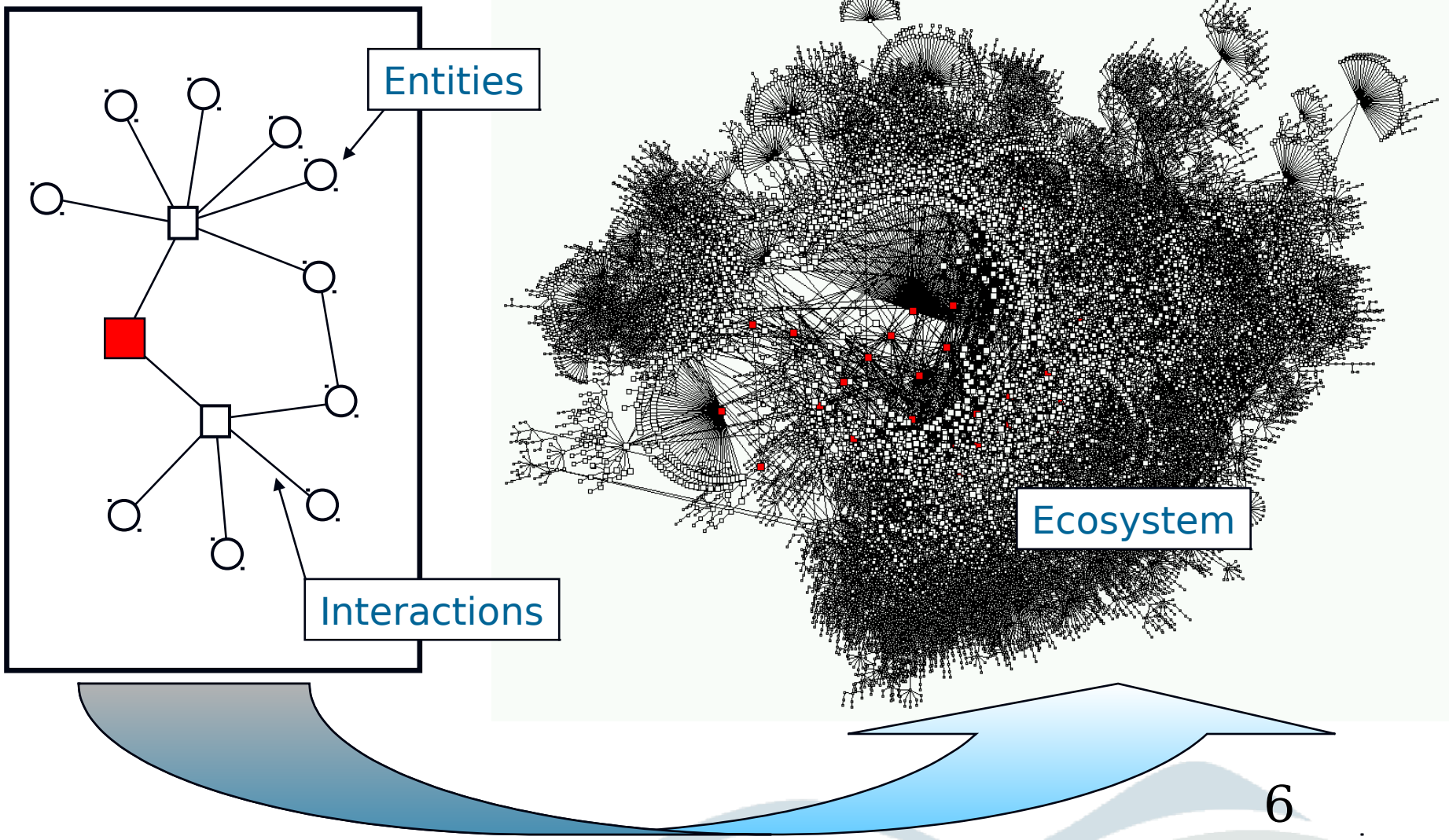
Ecosystem of Behaviors



Individual Actions lead to System Level Behaviors

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Complex Systems

A system is *complex* when:

1. It consists of a large number of elements
2. Significant interactions exist between elements
3. System exhibits *emergent behavior*: cannot predict system behavior from analysis of individual elements

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Inevitable: any complex system has loopholes

And loopholes can (and will) be exploited

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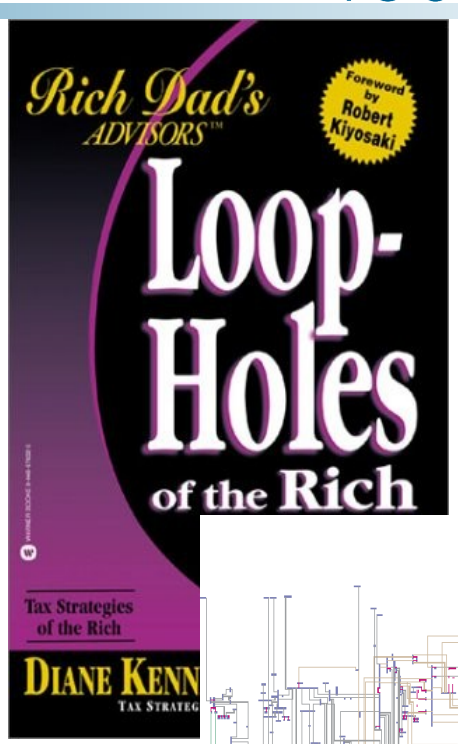
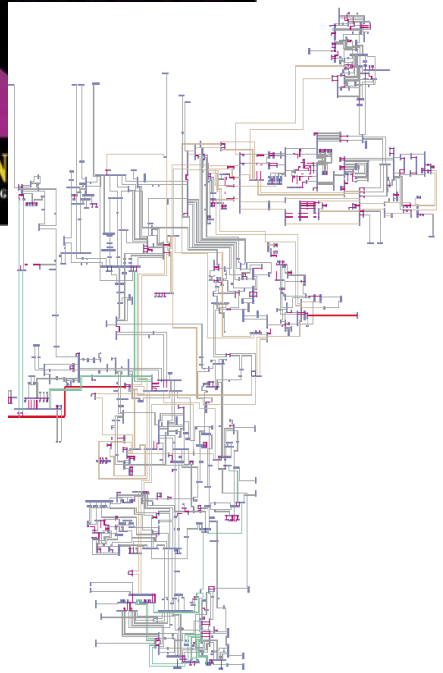
- Tax code
- Software
- Frequent flier programs
- Health care, Medicare
- 1996 Telecommunications act
- NBA rules
- Elections
- Power grid, water distribution





New York State power grid,
From Strogatz, Nature, 2001

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What can we do about it?

Depends on which side you're on!

Either way, you want to systematically discover the system's weaknesses

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Hints from Nature

Parasites

Viruses

Co-evolutionary arms races

Rapid evolution

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Evolutionary/Adaptive Testing

- Identify failure modes in complex systems
- Engineers can only test a small fraction of all possible configurations and damage scenarios
- Possible to find small investments that will dramatically improve robustness? i.e., better design

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Design Testing – Ship Systems

Firemain Segregation

Condition Zebra

USS Arleigh Burke

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Objectives

- Feasibility of evolutionary testing on a shipboard control system
- Modeling ship's firemain system with local valve controls
- Evolving *challenges*
  - Pipe rupture, e.g. from torpedo attack
  - Water demand, e.g. ballasting water

Problem Statement

- Use *evolutionary computing* to search vast space of possible challenges
- Identify particularly problematic combinations of challenges
- Study effects of random vs. correlated challenges

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Evolving challenges

Modeling the ship

USS Arleigh Burke firemain

Firemain Segregation

Condition Zebra

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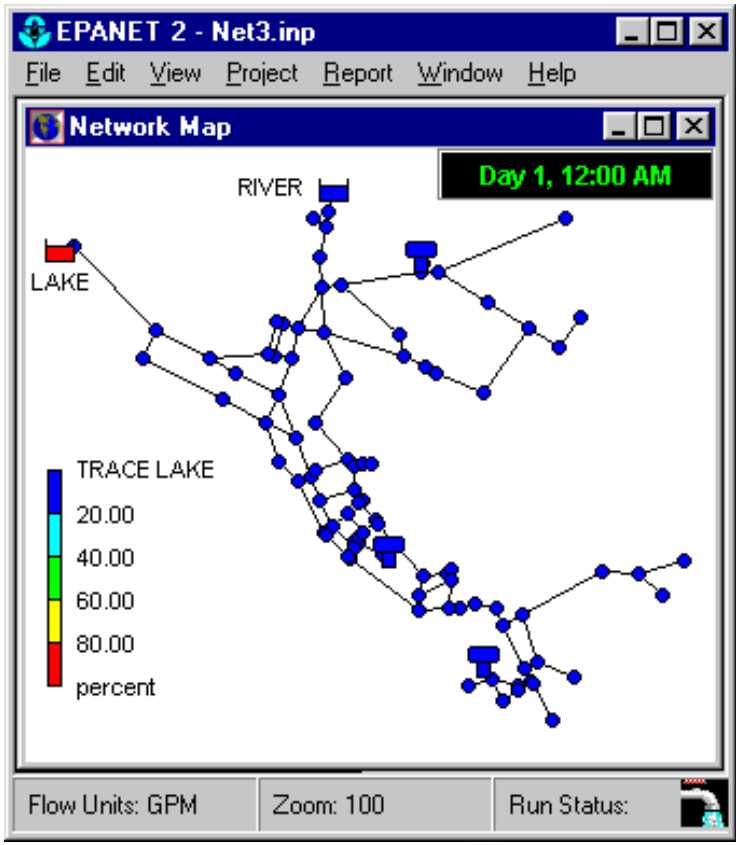
EPANET (Environmental Protection Agency)

- Model city water
- Any number of
  - Pipes
  - Pumps
  - Tanks
  - Valves
- Calculates steady state flows, pressures etc.
- Implement network in minutes
- Simple, local controls



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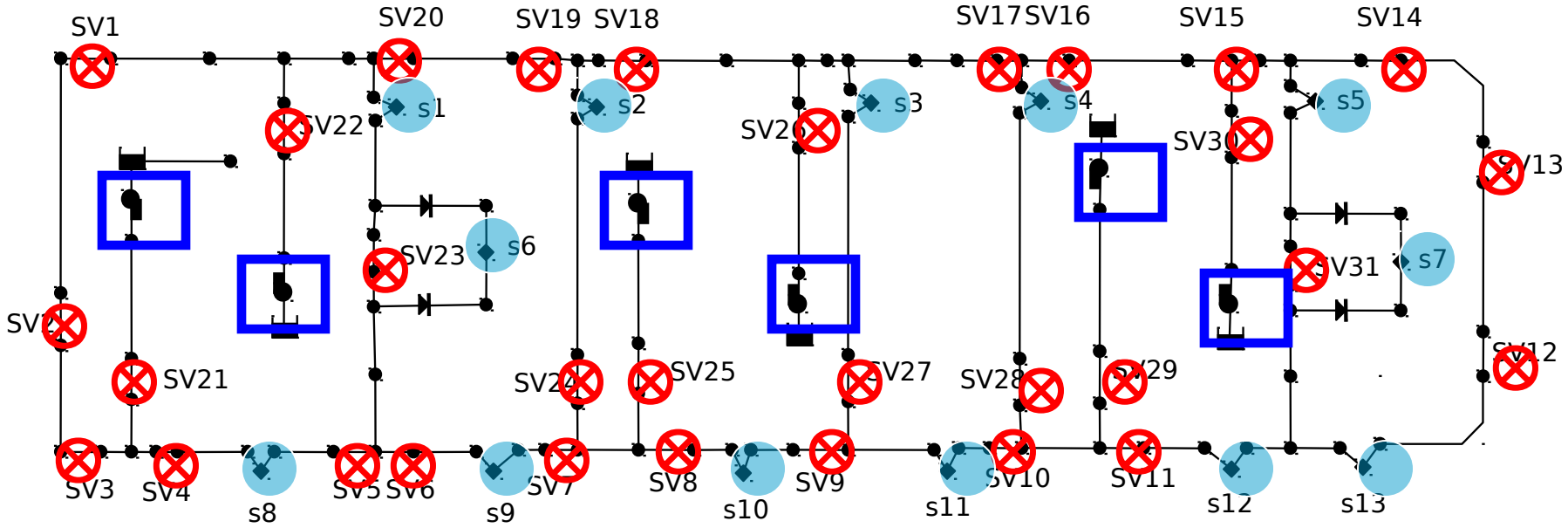
Scale model



Stop valve, under local control

Sprinkler valve

Pump, under local control

Challenges:

- **Pipe rupture—e.g. torpedo attack [63pts]**
- **Water demand—e.g. ballasting [49pts]**

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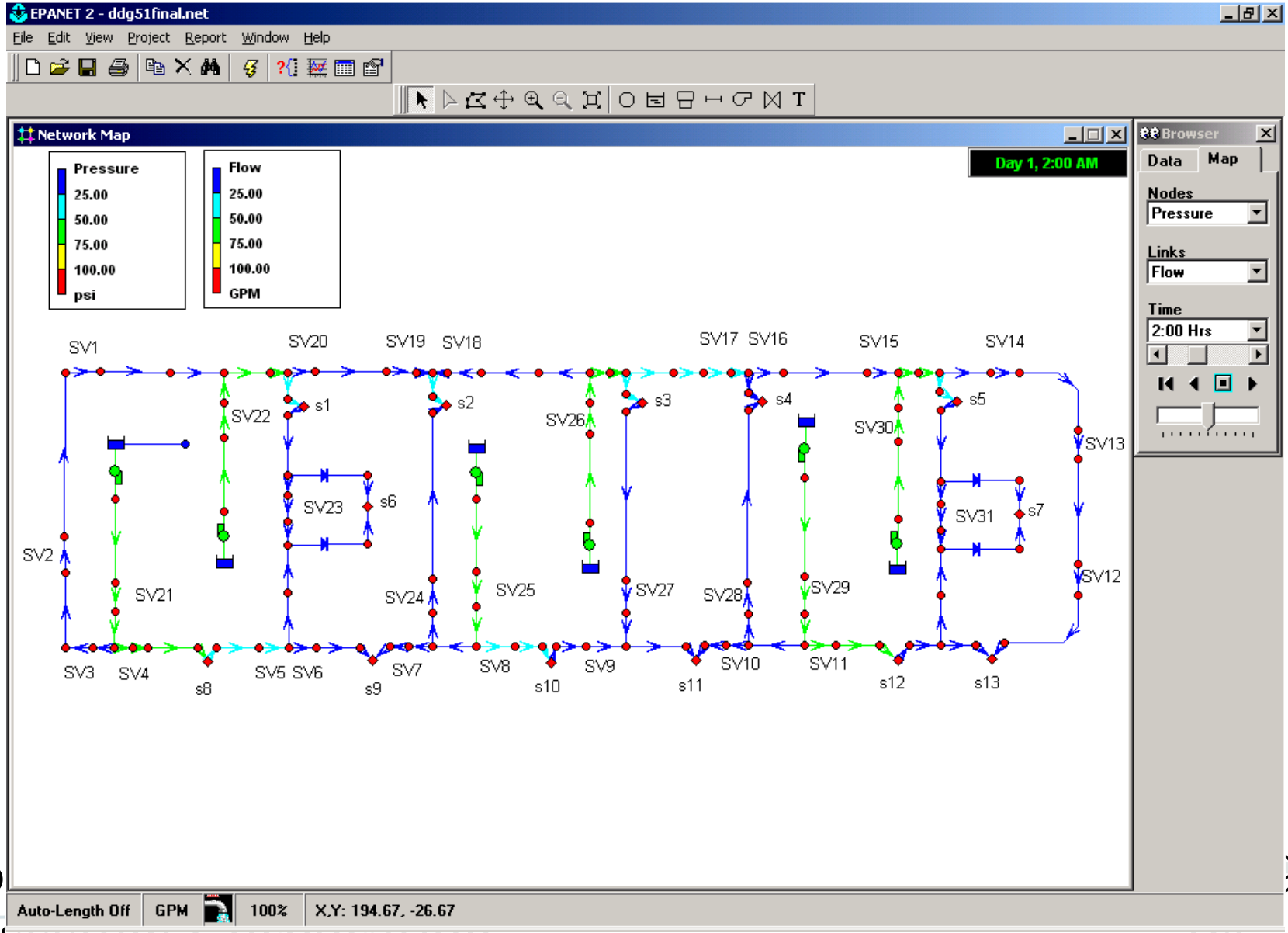
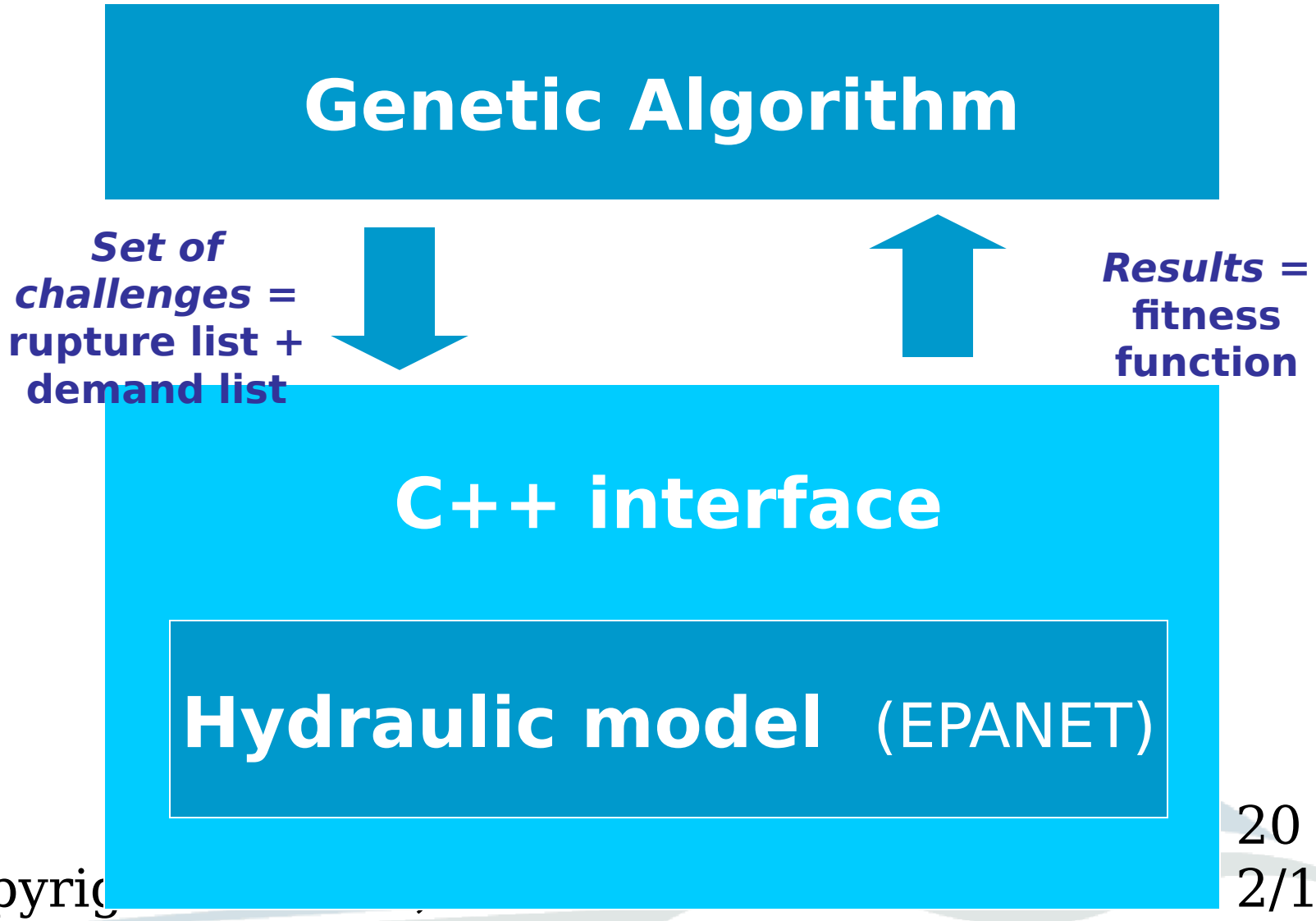
EPANET network



Implementation


Genetic Algorithm
Set of challenges = rupture list + demand list
Results = fitness function
C++ interface
Hydraulic model (EPANET)

Copyrig
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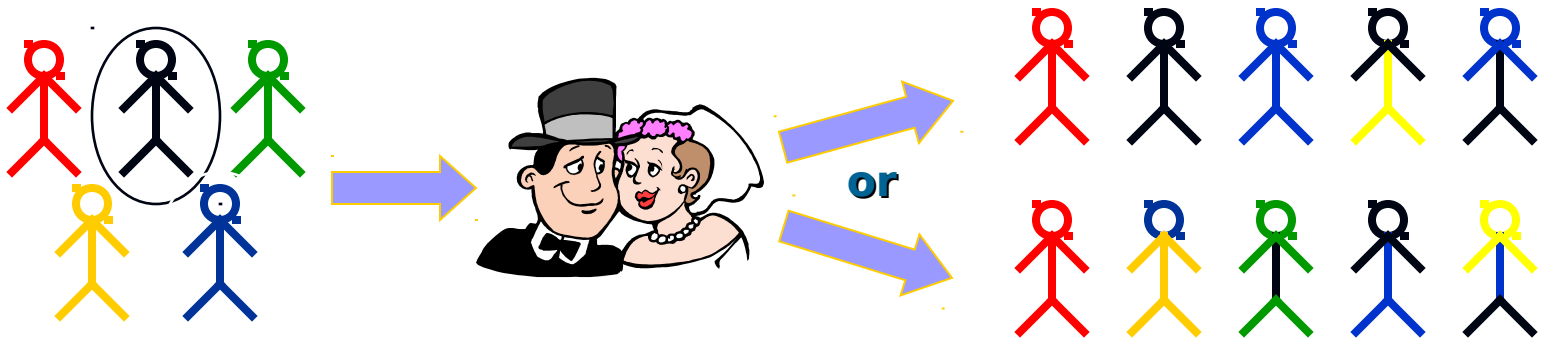
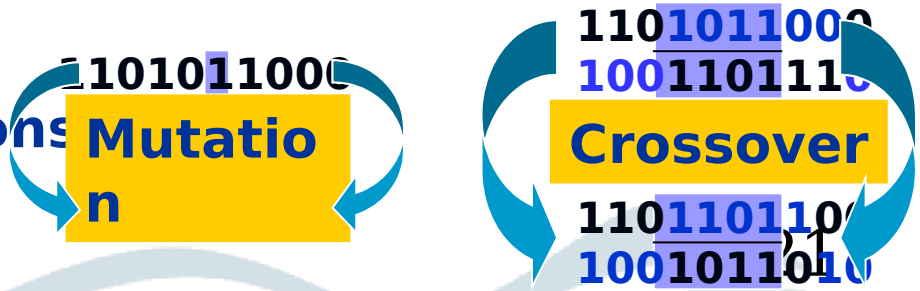
Evolutionary computation

Individuals are represented by genetic string

1101011000…



Two genetic operations



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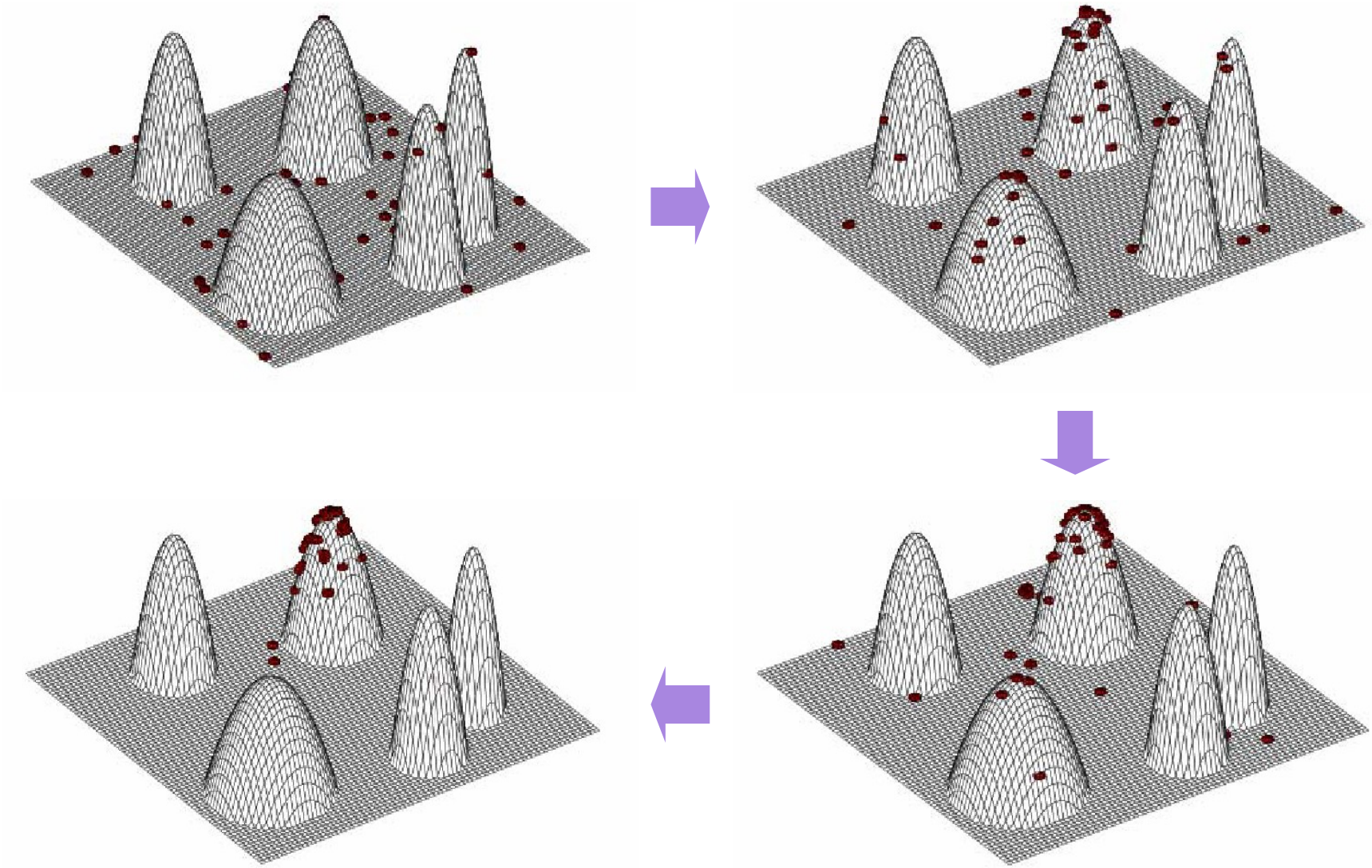
Evolving challenges



From Ken de Jong

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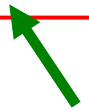
Genotype: Specifies set of challenges

Rchromosome [list of all 63 rupture locations]

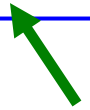
`0000100000000001000 … 000010000`



Rupture location 5 [time 0, emitter coefficient 2]

Dchromosome [list of all 49 locations where water can be draw

`0100000000000000010 … 000010000`



Draw 500 gallons per minute from location 2

Unconstrained state space = $2^{(63+49)}$

$\approx 10^{34}$

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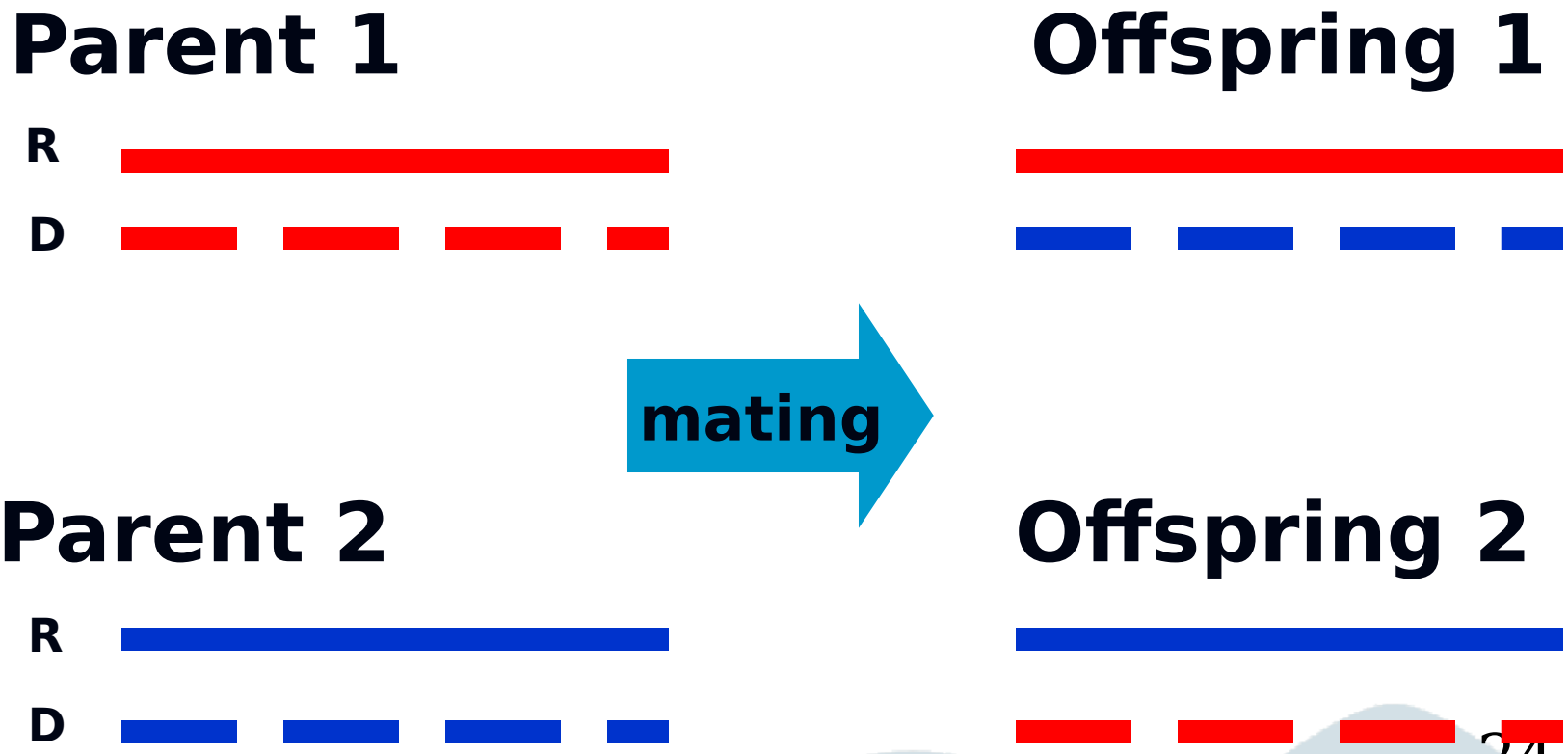
Meiosis : form of genetic crossover



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Mutation : rupture nearby pipes instead

Rchromosome

`0000100000000001000 … 000010000`

1. **Select one of the 1s from the R chromosome**
2. **Get list of physical distances to all other rupture locations from proximity matrix**
3. **Take *reciprocals* of distances; sum them; divide each by sum**
4. **Choose new location probabilistically from this normalized vector**

Proximity matrix

	1	**2**	**.**	**.**	**.**	**63**
1	0	105	307	226	178	300
2	**105**	0				
.	307		0			
.	226			0		
.	178				0	
63	300					0

e.g. rupture point 1 and rupture point 2 are 105 feet apart

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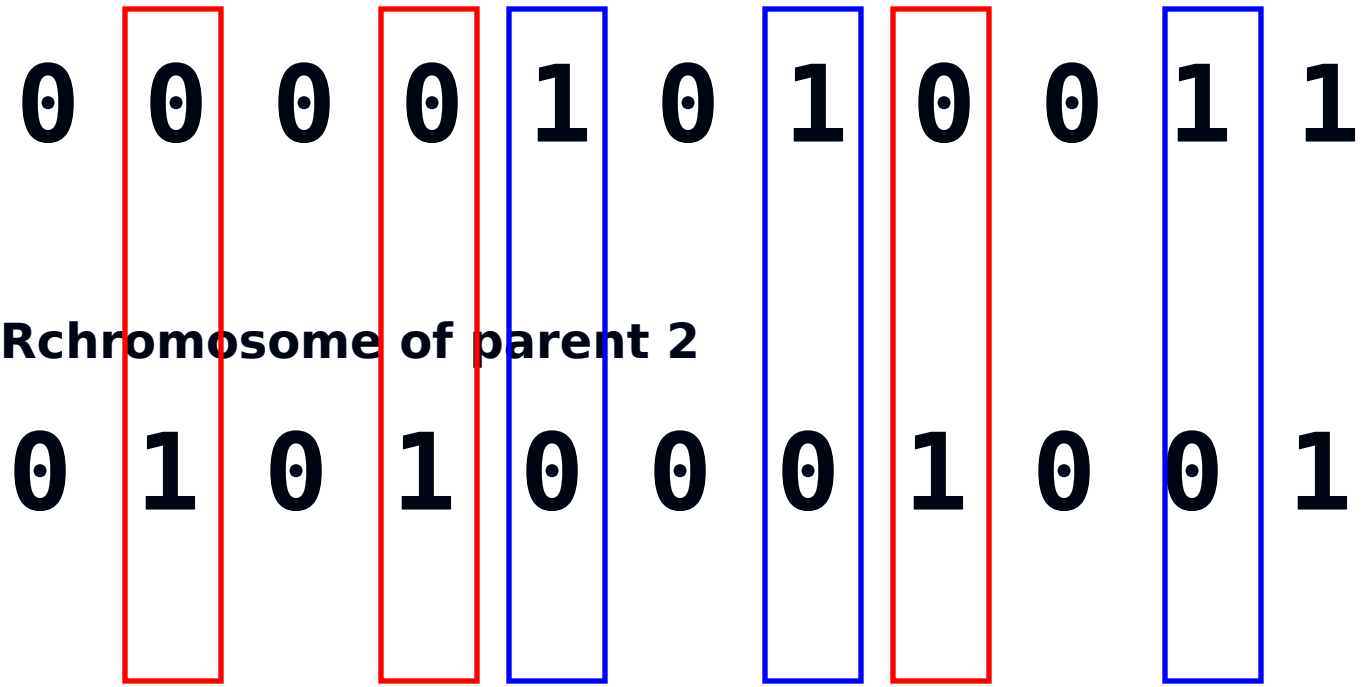
Crossover : while conserving #ruptures

Rchromosome of parent 1



Rchromosome of parent 2

3 pairs available for crossover

1. **Pick a red pair and a blue pair at random**
2. **With Probability 0.5 swap them [change 1 → 0 and 0 → 1]**
3. **Do for all pairs (i.e. all remaining reds + their blue**

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Parameters

- **Population size** **50**
- **Elite size** **10**
- **Number of Ruptures** **1–3**
- **Number of Demands** **0–2**
- **Mutation Probability** **0.5**
- **Meiosis Probability** **0.5**
- **Crossover Probability** **0.5**
- **Fitness metric** **9 to choose from**
  - **“Deadwater” length**
  - **Maximum pump flow**

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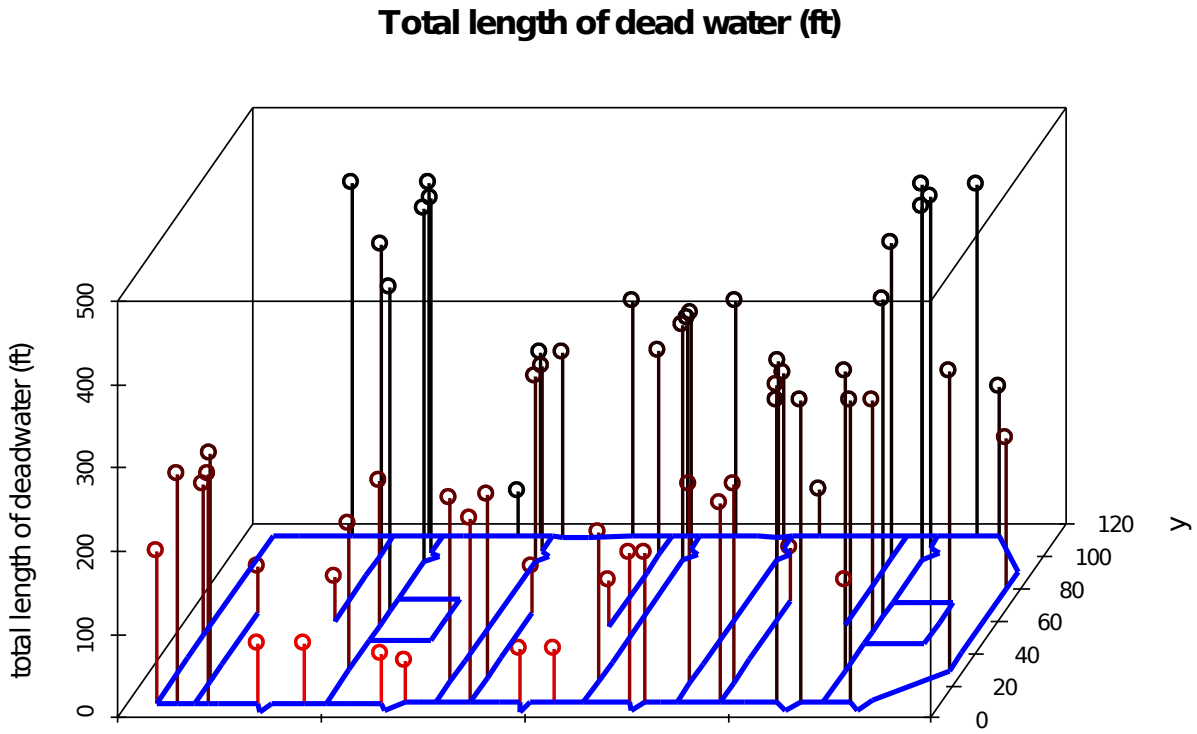
Results:
Finding worst case ruptures

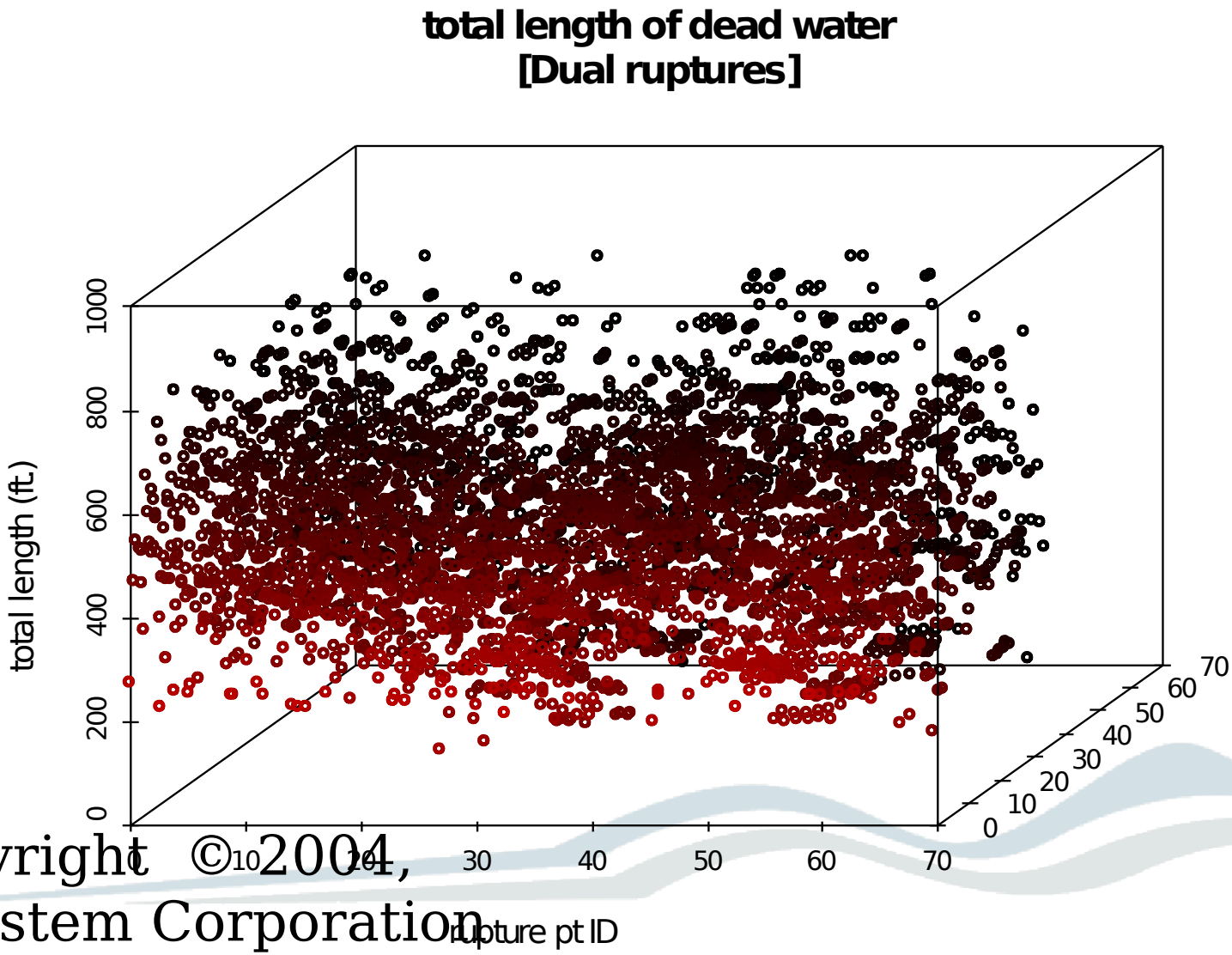
Single Ruptures



Conclusions:

1. **Several “sensitive” areas of the ship, mostly on the port side, fore and aft.**
2. **Four equivalent “worst” locations—GA returns *all* of them simultaneously**

Dual Ruptures



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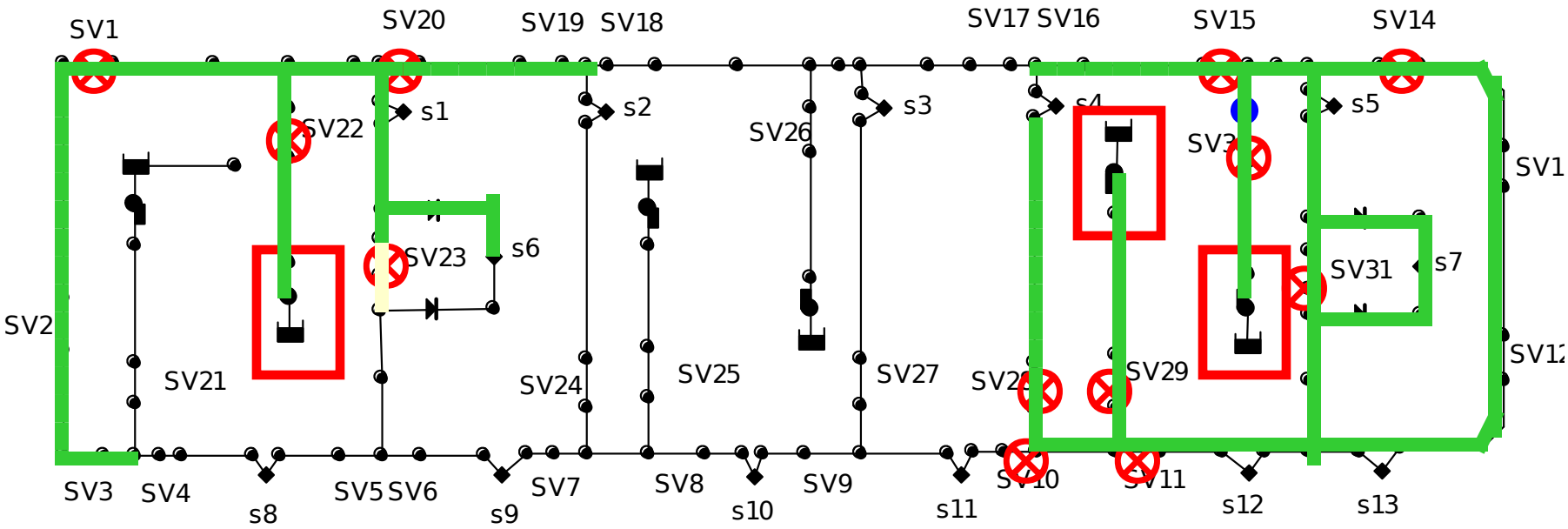
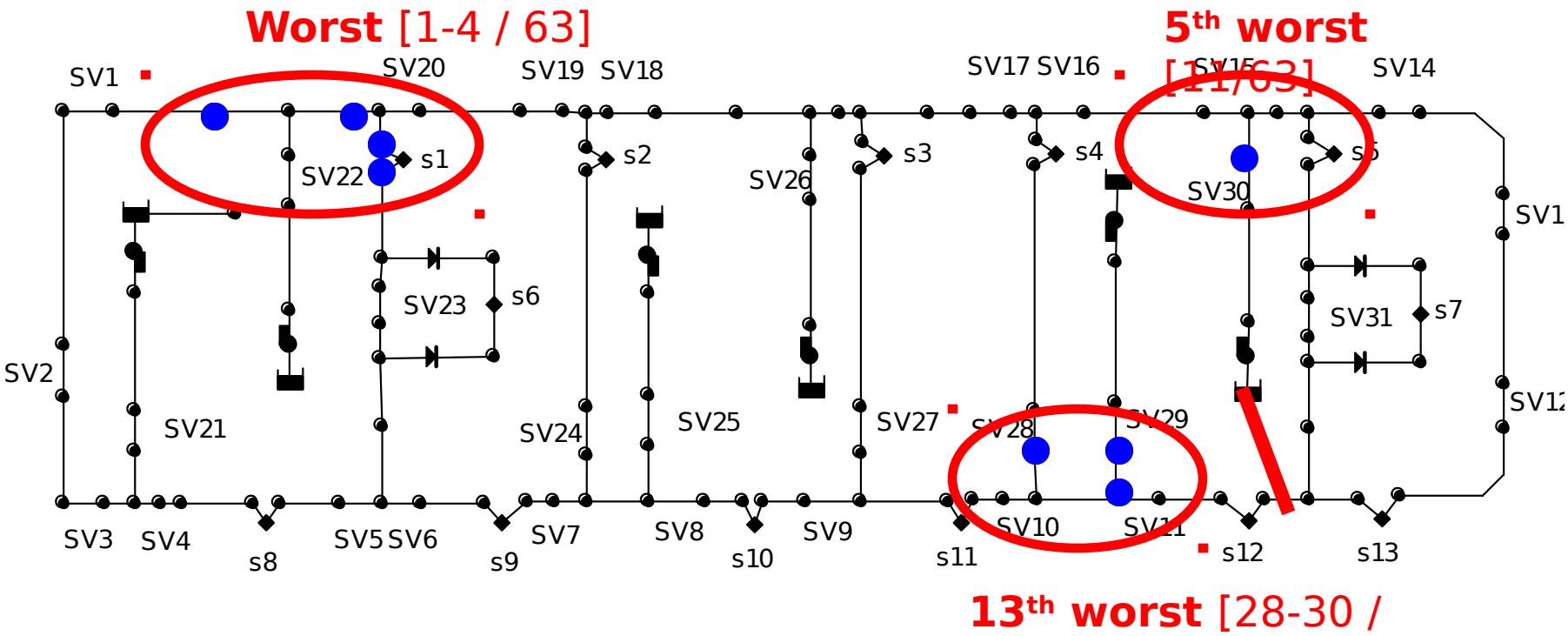
Triple Ruptures



Conclusion:

- **GA found these worst cases < 3min (vs. systematic search: > 3 hrs)**
- **GA took median of 49 generations, i.e. ≈ 1 % of state space**

Triple vs. Single Ruptures



Conclusion:

- **No: worst 3 pt rupture involved “insignificant” locations, low down on list**
- **r56 vulnerable: add in pump → starboard loop riser?**

Results:
Threshold search

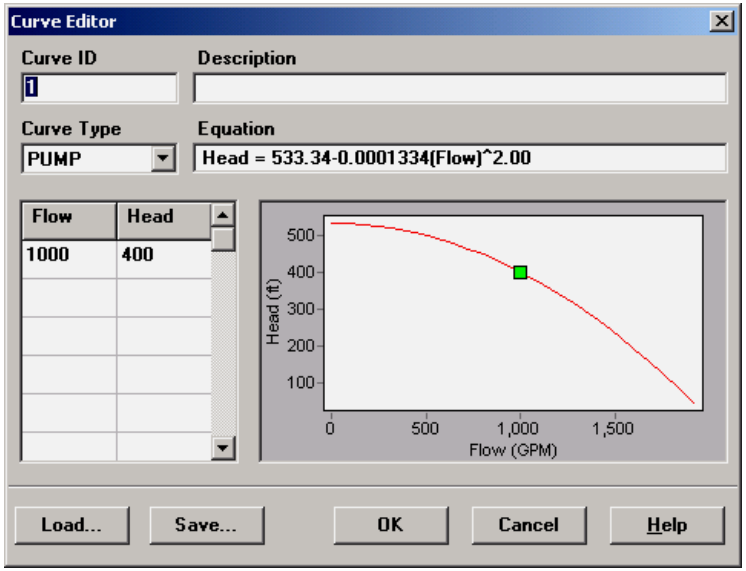
Threshold search

Component constraint

- Pump flow rate
- Max. safely: 1000 gpm
- Threshold 1000

> 1500: dangerous
> 1250: warning
> 1000: overheating

- GA searches and lists all results > threshold



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Threshold search

- **2 ruptures ⇒ (6-2) × 1500 = 6000 gpm**
- **2 demands 2 × 2000 = 4000 gpm**

Spare capacity: 2000 gpm

- **Set threshold @ 1000 gpm, see what happens…**

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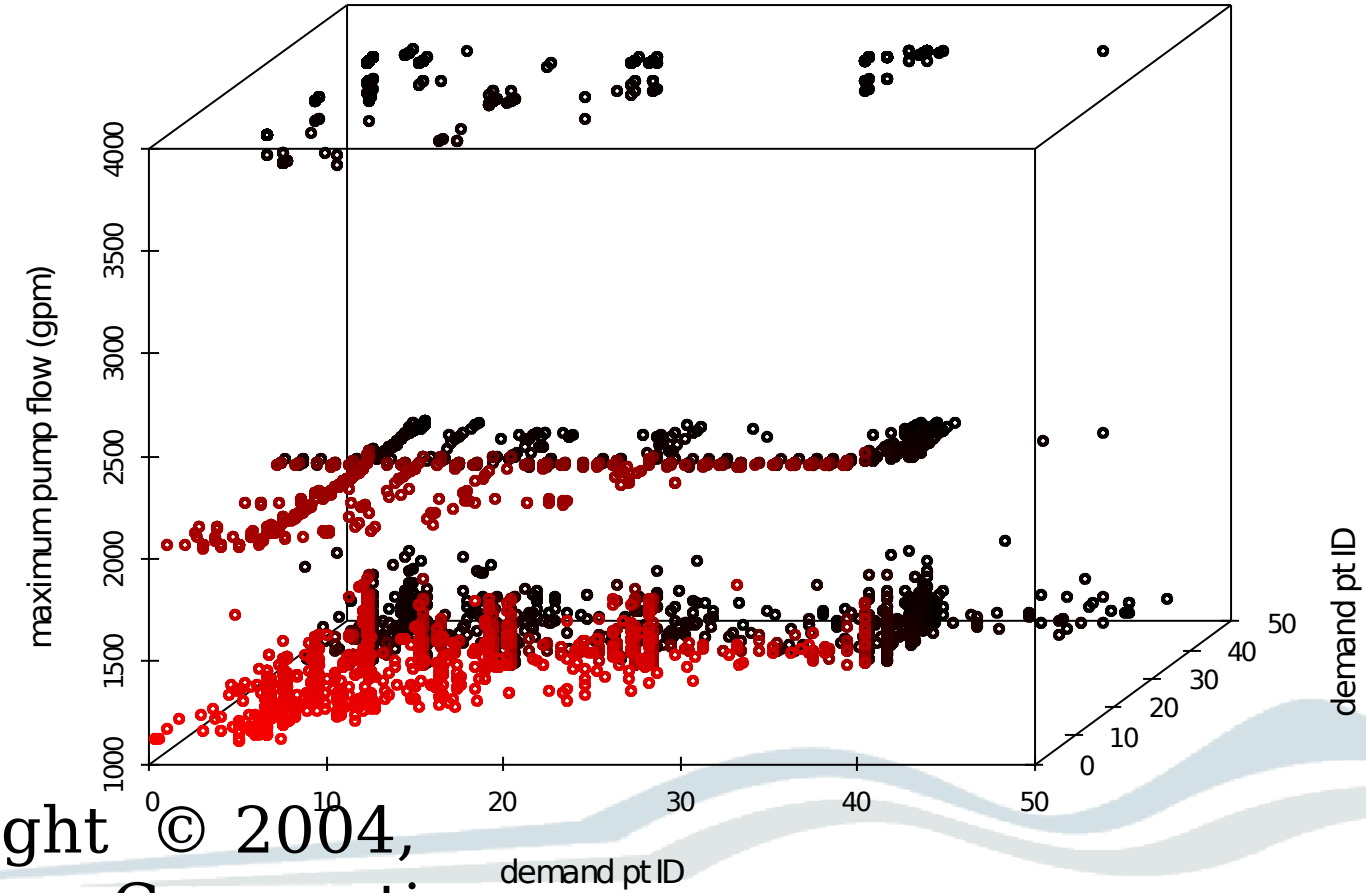
Results

Conclusions:

- **1. Some huge values (4000 gpm)**
- **2. Damage Control (DC) protocol: no-go locations for drawing off water**



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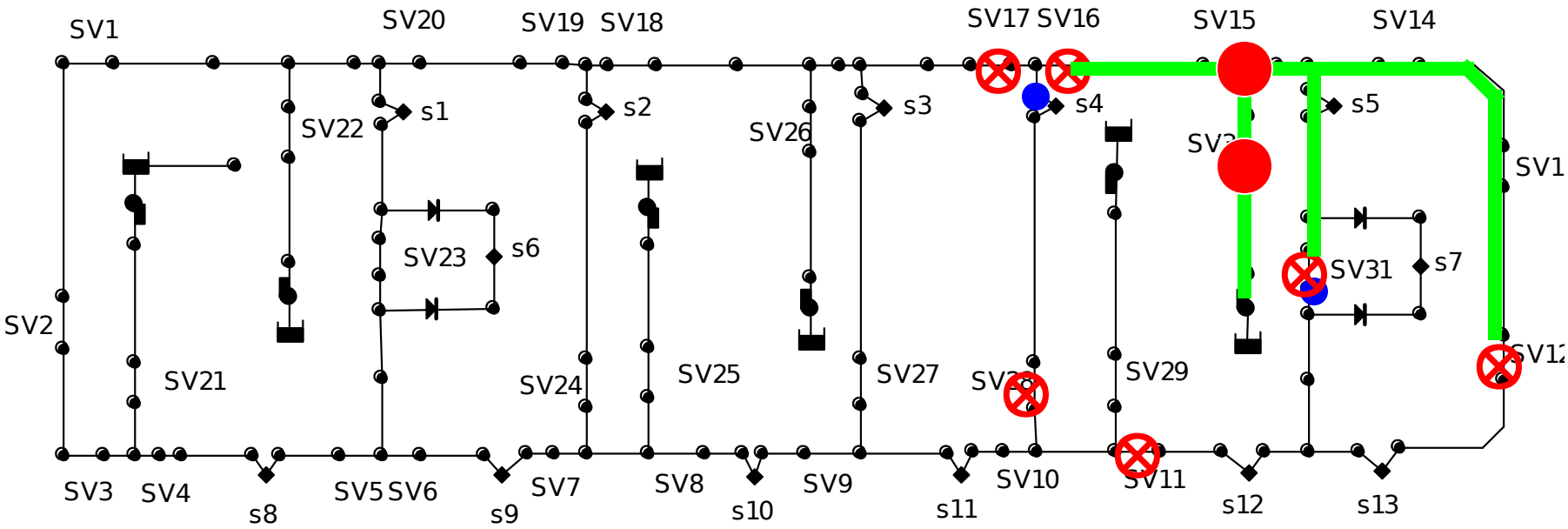
Why was value so high?



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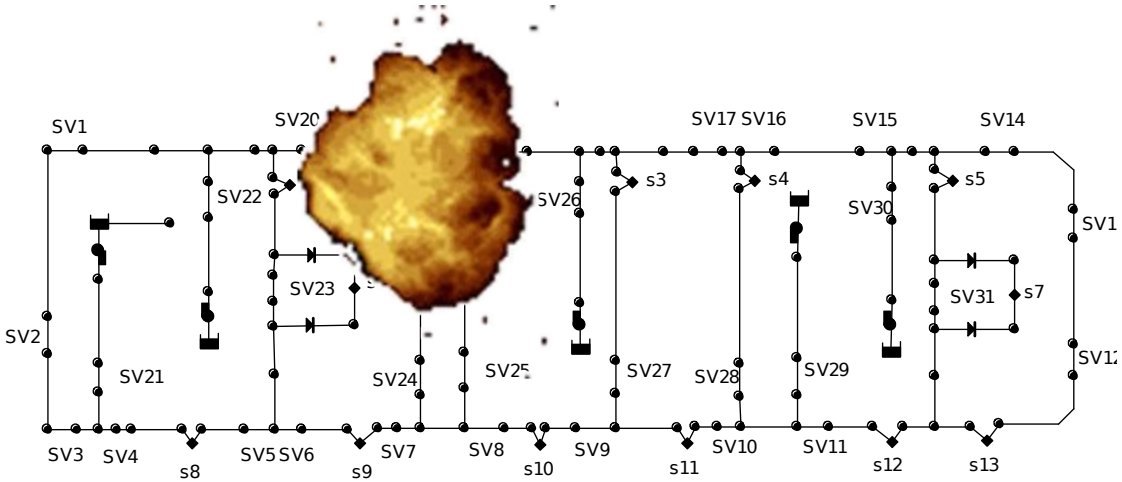
Results:
Correlated damage

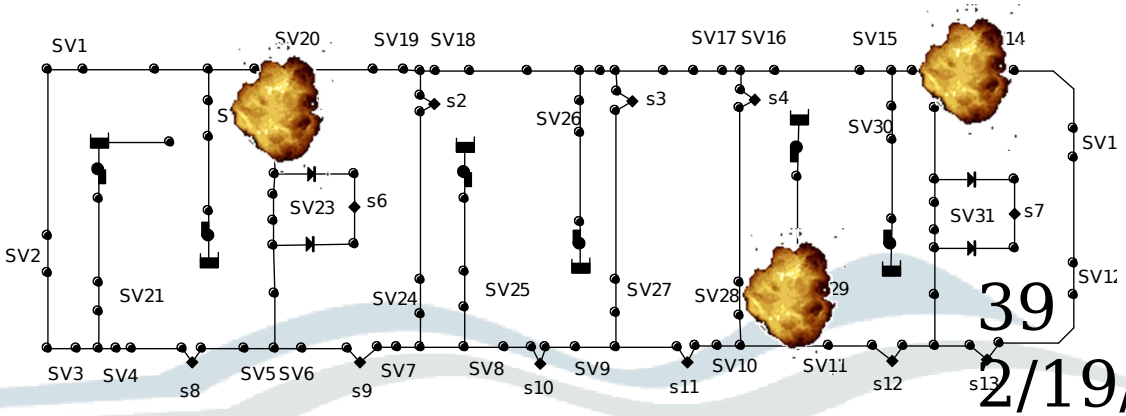
Correlated vs uncorrelated damage

***N* ruptures clustered**

(take N - 1 nearest locations)



***N* ruptures uncorrelated**



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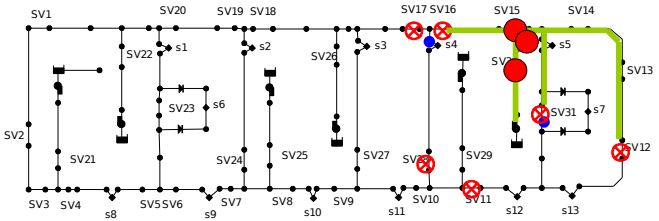
Results:
Operations
- Condition Zebra

Condition zebra

⇒ partition ship into 2 isolated mains: part & starboard

Results

Why was value so high?



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X-ray *vs.* zebra

clustered ruptures

2 demands

No. ruptures	Maximum pump flow	
	X-ray	Zebra
1	367.68	1025.27
2	1025.27	1025.27
3	1025.27	1025.27

Conclusion:

- **Zebra has a large effect for MPF only with single ruptures**

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Conclusions

- GA proved itself in optimizing worst case scenarios for both correlated and uncorrelated damage
- Some surprising results: e.g. worst 3pt rupture involved an insignificant rupture location halfway down list
- Huge potential for searching for bounds of working conditions [threshold search]
- Tool for design of more robust systems and control strategies (e.g., where to add pipes, where NOT to draw water, ...)

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Application of

- Beyond simple challenges: dynamic challenges, correlated challenges
- Identifies risk mitigation strategies
- Huge potential for searching for bounds of working conditions

Can be applied to:

- System Concept Designs
- Existing Systems
  - Software/Hardware
- System Health and Monitoring

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Questions?

Paper is available, for more information, contact:

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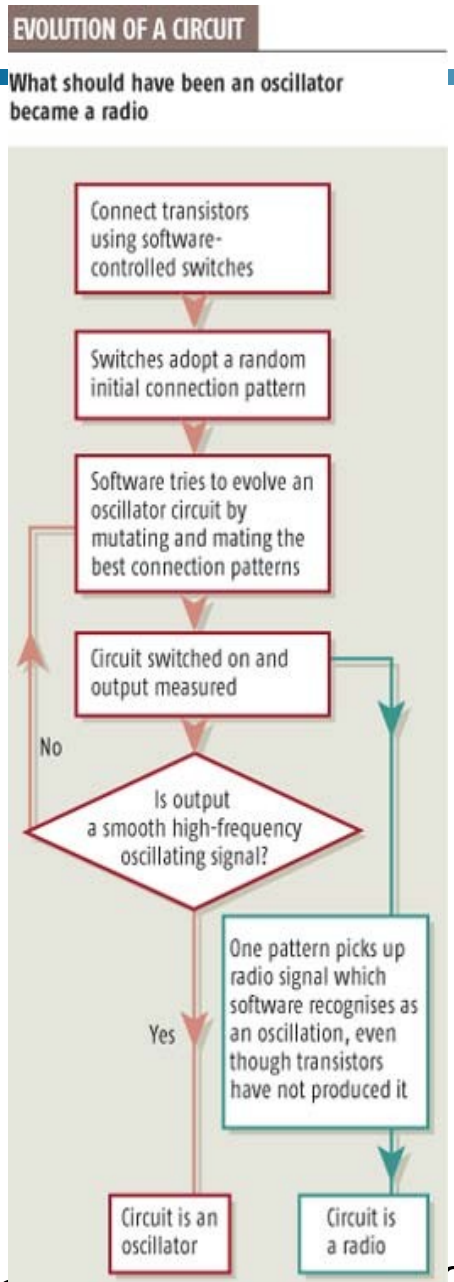
EVOLUTION OF A CIRCUIT
What should have been an oscillator became a radio
Connect transistors using software-controlled switches
Switches adopt a random initial connection pattern
Software tries to evolve an oscillator circuit by mutating and mating the best connection patterns
Circuit switched on and output measured
No
Is output a smooth high-frequency oscillating signal?
Yes
One pattern picks up radio signal which software recognises as an oscillation, even though transistors have not produced it
Circuit is an oscillator
Circuit is a radio

- In 2002, Paul Layzell and Jon Bird of U. Sussex in Brighton, UK, tried to design an oscillator using evolutionary computation.
- They discovered an intriguing arrangement of transistors that produced an oscillating output.
- But the circuit was not an oscillator.
- They had evolved a radio receiver that was picking up a signal from a nearby computer and delivering it as output.
- In essence, the evolved circuit had found a loophole in the experimental setup, and relayed oscillations generated elsewhere rather than generating its own.

Source: New Scientist.com, 31 August 2002